How to impart tacit knowledge: "Blending Chess and Chemistry"

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Abstract
Retrosynthesis has been likened to the game of chess. There are relatively simple rules to learn, but only through experience and practice can a learner acquire the tacit knowledge required for mastery of the subject. This makes it a challenging topic to teach effectively to a large and diverse cohort of learners. Lectures are a good way of transmitting knowledge, but do not provide the engagement and training that is essential in developing a deep understanding of retrosynthesis. Therefore, students tend to struggle to achieve success in this topic. This project aimed to alleviate this problem by producing online learning resources to be combined with traditional face-to-face teaching methods to develop a blended learning approach. These resources included animated videos, quizzes, worked examples and other interactive learning materials. Analysis of examination results and learner feedback showed that the supplementary resources not only improved student performance and understanding, but also provided a more satisfactory learning experience. External evaluation suggested that the learning package has significant potential and development should be continued. The package of learning resources can be viewed online at: people.bath.ac.uk/ch3jhm

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The Challenge of Retrosynthesis
Retrosynthesis has typically been considered a very challenging topic by both students and lecturers. There are a number of reasons why this might be the case.

It is counter-intuitive, as it requires students to start from a target molecule and break it up, thinking backwards in a strategic fashion. This is the opposite process to all the organic chemistry they have previously learnt.

Retrosynthesis has also been likened to the game of chess[1]. In chess it is easy to learn how the pieces move so you can begin playing, but you cannot become a grandmaster simply by possessing this knowledge. You need practice and experience to develop a full understanding of the underpinning strategies. Similarly in retrosynthesis, you need to know the rules of how functional groups react to be able to design syntheses, but this knowledge alone will not enable you to carry out retrosynthesis on complex molecules. Again, practice and experience are required to formulate a deeper understanding and this cannot simply be passed on by an expert.

As a result, the ability to perform retrosynthesis can be classified as tacit knowledge. This term was first used by Polanyi[2] to describe knowledge that allows an individual to perform a certain task, without that knowledge being easily transferred or learnt without the learner engaging in the activity. So, for retrosynthesis, it is not possible just to learn from lectures and textbooks, practice is essential to imbed the rules and theories learnt as an understanding of the topic and to help students develop the skills required to go with that understanding.

Current Teaching Methods
At the University of Bath, retrosynthesis is currently taught through a course of lectures, backed up by workshops and tutorials. Lectures are the most prevalent teaching method within Higher Education and are firmly imbedded within the traditions of university teaching[3]. Lectures are considered to be the most effective and efficient way of delivering content to large numbers of students in a short amount of time[4]. As a result, they are destined to remain an important part of the teaching within universities.

However, whilst lectures have been found to be an effective method of transmitting information, they are not as good for promoting thought or teaching behavioural skills[5]. They are also a passive learning experience, not giving students necessary opportunities to actively engage with the material and put what they have learnt into practice[6].

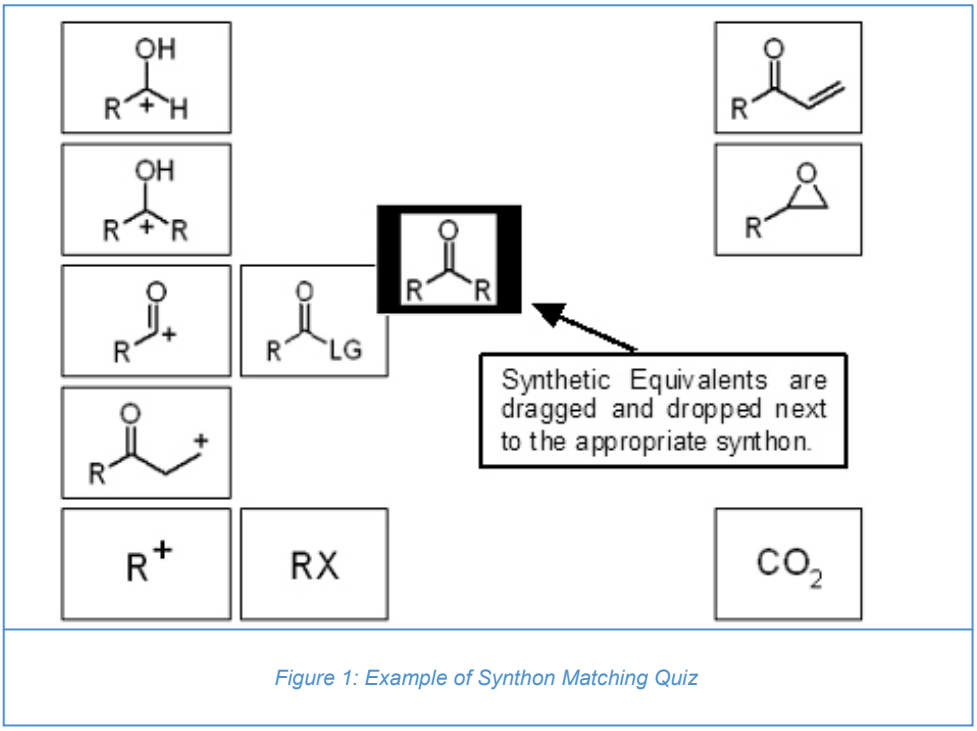

Figure 1: Example of Synthon Matching Quiz

It is therefore important to consider how the learning experience can be enhanced around the framework of lectures. For this project, consideration was given to how other teaching methods can be combined with lectures to enrich the learning experience for students. The main focus was on combining traditional, lecture-based teaching methods with online learning to provide a blended learning approach.

A blended approach can enhance the learning experience for students and improve their comprehension of a topic. Significant variety can be introduced into the learning materials that are provided, catering to the differing learning needs of students. The blended learning approach also allows flexibility in relation to both time and location, giving students the opportunity to learn at the pace and in the environment that they find most effective. Students enjoy greater control over their own learning, and are able to choose those resources that assist them most[7,8].

For this project, online learning resources were made available to students through Moodle, the virtual learning environment (VLE) supported by the University of Bath.

Project Aims

The project was divided into three sections: Exploratory Study, Resource Development and Development Study. The Exploratory Study aimed to identify the extent to which students struggle with the retrosynthesis course and the topics they find most problematic. The Resource Development stage involved the production of online learning materials to enhance the teaching and learning of retrosynthesis. The Development Study aimed to evaluate these resources from both a student and teacher perspective.

Exploratory Study

The Exploratory Study involved the use of workshops and tutorials to assess the understanding that students had developed during the normal lecture course and identify the areas that were most challenging. Students were asked to attempt retrosynthesis problems and their solutions were analysed. Through the answers students gave, observation of the student activity, the issues that were raised during the workshops, and informal student feedback, a picture of the problems students encountered and the topics with which they struggled was formed. A questionnaire was also used to obtain student opinions on their own comprehension and the resources they felt would be most helpful.

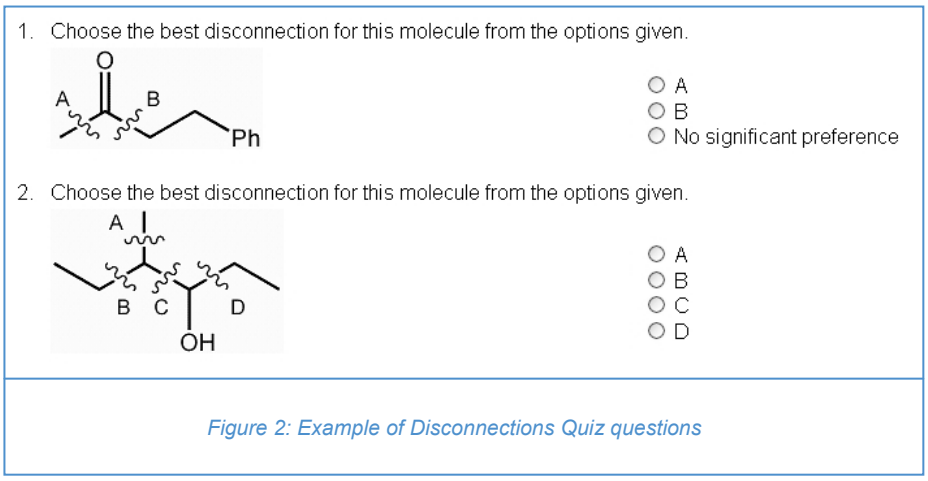

Figure 2: Example of Disconnections Quiz questions

Additionally, trial resources, including animated videos, were made available on Moodle and the students asked to give feedback in order to assess how such resources would be received.

The results showed that while students managed to grasp the basic principles of retrosynthesis, their knowledge and understanding was lacking in a number of areas, in particular the following:

- Remembering the synthetic equivalents to certain synthons
- Remembering reagents for FGIs (Functional Group Interconversions)
- Choosing the best disconnection to make to simplify a molecule
- Identifying selectivity issues

Therefore, these were areas on which the development of additional resources was focused. The initial resources that had been made available on Moodle were well received by the students. They liked and made of use of these resources and were positive about the usefulness, quality and pace of the videos. Therefore, videos seem to be an effective way of conveying concepts and working through question answers with students. However, support for the videos was not unanimous, and so it was important to include a variety of resources in order to cater to the learning needs of all.

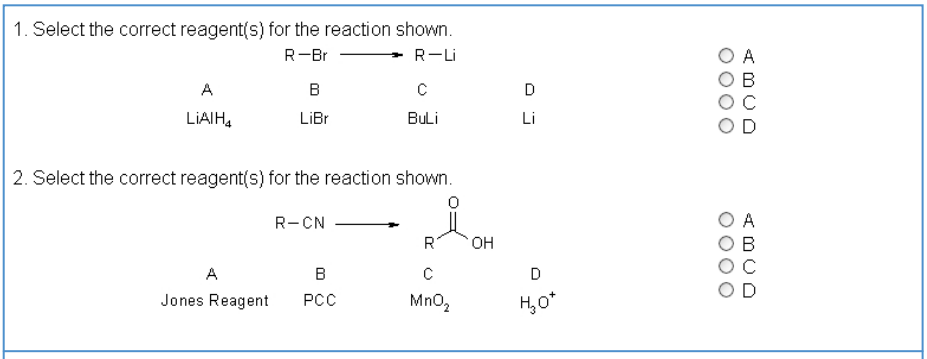

Figure 3: Example of FGI Quiz questions

Resource Development

At this initial stage of the project, resources for the first two lectures of a six lecture course were developed, along with some additional revision resources. The learning materials included the following:

- *Pre-lecture Lessons and Quiz* – a set of lessons covering the basic prerequisite knowledge for students to go through before participating in the lecture course, with a quiz to test their understanding of these areas.
- *Lecture Slides* – PowerPoint slides for use in lectures, around which the package is based.
- *Narrated Lectures* – the same lecture slides with voice narration added, so students could use them as part of an independent learning package.
- *Synthon Matching Quizzes* – quizzes that require students to match real reagents to synthons, to help them become familiar with these relationships – see Figure 1.
- *Disconnections Quiz* – a quiz requiring students to choose a disconnection from a number of options within a compound, to help them develop an understanding of the strategies for selecting the optimum disconnection – see Figure 2.
- *FGI Tool and Quiz* – a tool that allows students to find the reagents for carrying out a certain disconnection, with an associated quiz to test their knowledge – see Figure 3.
- *Worked Examples* – animated videos working through solutions, so students can see examples of how to tackle similar problems.
- *Practice Questions* – problems for students to attempt, with animated videos that take them interactively through the solutions, asking them questions on the way – see Figure 4.
- *Selectivity Videos* – animated videos taking students through the major selectivity issues covered in the course, with interactive questions to cement the understanding – see Figure 5.

Development Study

The majority of the resources were made available to students as they prepared for a summative assessment on retrosynthesis. A number of methods were used to ascertain the effectiveness of the resources from a student perspective, in terms of their opinions, usage and performance. These were Moodle user statistics, Moodle-based and paper-based questionnaires, student interviews and examination results. In order to gain a teacher perspective on the resources, academic staff from other Higher Education institutions were contacted and invited to evaluate the resources.

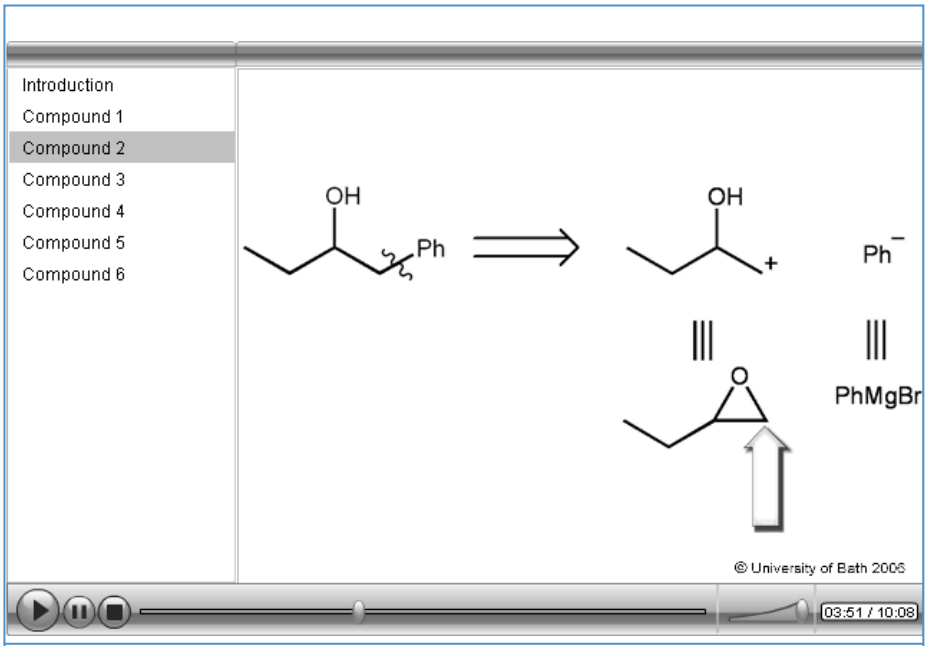

Figure 4: Screenshot of animated video solution to Practice Question

A significant improvement in exam performance was observed over the previous year, where no online learning resources were available. The average mark increased from 50% in 2006 to 68% in 2007. As Figure 6 shows, more than half of the students achieved a First Class grade in 2007, and fewer failed than in 2006.

There was a high uptake of the resources among students, with the vast majority making some use of them. Those students who used the resources performed significantly better in the exam, averaging 74%, compared to 50% for those students who did not make use of any of the resources.

The feedback received from students was very positive, and all the students who used the resources felt they had a positive impact on their exam performance. This was exemplified by some of the comments made by students, with the interactivity being highlighted as particularly important:
"The extra support on Moodle was helpful and much appreciated."
(Laura Fedorciow, BSc Chemistry with Management and SSLC Representative).
"The interactive format of this revision material was a welcome break from ordinary revision, and was much more effective than just reading the relevant information."
(David Cutcliffe, MChem Chemistry).

The external academic staff also rated the resources highly and felt the blended learning package would be of significant benefit to students learning retrosynthesis:
"I have lectured on [retrosynthesis] *for many years and I find this package very good…This package will help the students a lot."*
(Dr Paul Jenkins, Senior Lecturer, Department of Chemistry, University of Leicester).

They highlighted the importance of equipping students to continue studies outside lectures, in an environment they can control, but still with guidance and support:
"They allow students to go away and think out the steps needed for synthesis problems at their own pace – giving time for reflection which formal lectures do not give."
(Dr Hazel Wilkins, Lecturer, School of Life Sciences, Robert Gordon University).

There was unanimous support among the evaluators for the full development of the resources, but they identified a number of areas where improvements could be made and highlighted the need for a rigorous evaluation:
"What is needed are packages like this one that are then evaluated."
(Dr Bill Byers, Senior Lecturer, School of Health Sciences, University of Ulster).
"I would encourage you to continue with this development, we would certainly use it if it was available at a reasonable price."
(Dr Paul Jenkins, Senior Lecturer, Department of Chemistry, University of Leicester).

Conclusions
The process of learning is complex, and unique to each individual learner. Therefore, the task of imparting knowledge and promoting understanding in a large group of learners is a difficult one. It is made all the more difficult when the knowledge being conveyed is tacit in nature and the learners do not have a deep comprehension of the underpinning principles of the topic. This is the challenge faced when teaching retrosynthesis, which is akin to chemical chess, to a diverse body of learners.

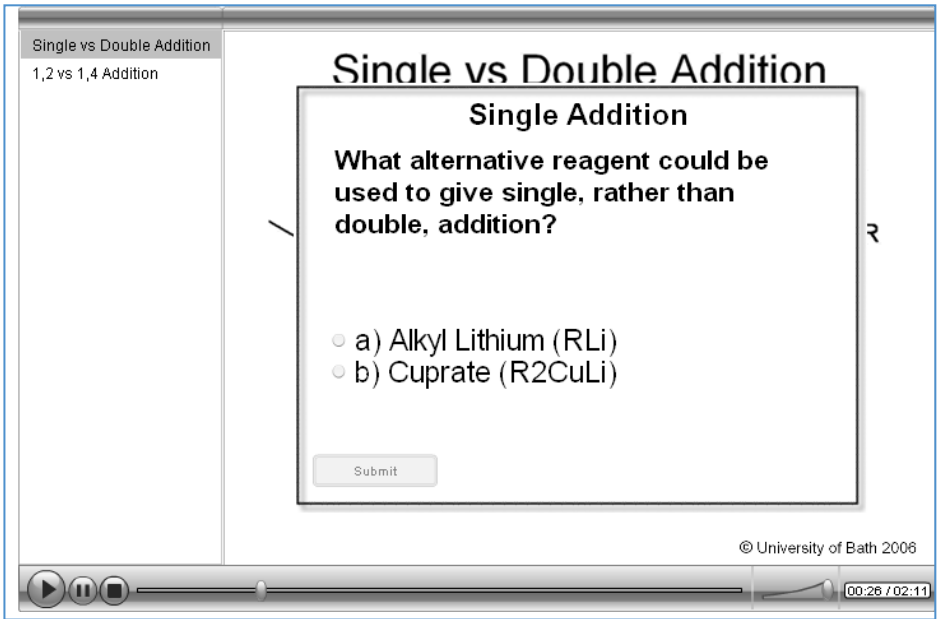

Figure 5: Screenshot of interactive question within a Selectivity Video

This research study has shown that success can be achieved by taking a blended approach to the teaching of this topic. The combination of face-to-face and online aspects of learning had significant positive effects on learners' understanding and ability to tackle retrosynthesis problems. Learners can engage more dynamically with the material and construct concepts on the basis of experience. The interactivity of the delivery methods increases motivation and focus, thus engendering more effective learning. Learners also benefit from extra freedom and flexibility to control their own learning.

The results of these enhancements to the learning process were two-fold:

- Improved examination performance, an indicator of comprehension
- Increased satisfaction with the learning experience

The positive results from the learner perspective were echoed by the feedback received from external evaluators. Individuals involved with the teaching of retrosynthesis suggested the blended learning package had significant potential and resource development should be continued. Therefore, it is intended that the development of this package will continue, and once complete it will be fully evaluated and made available to Higher Education establishments.

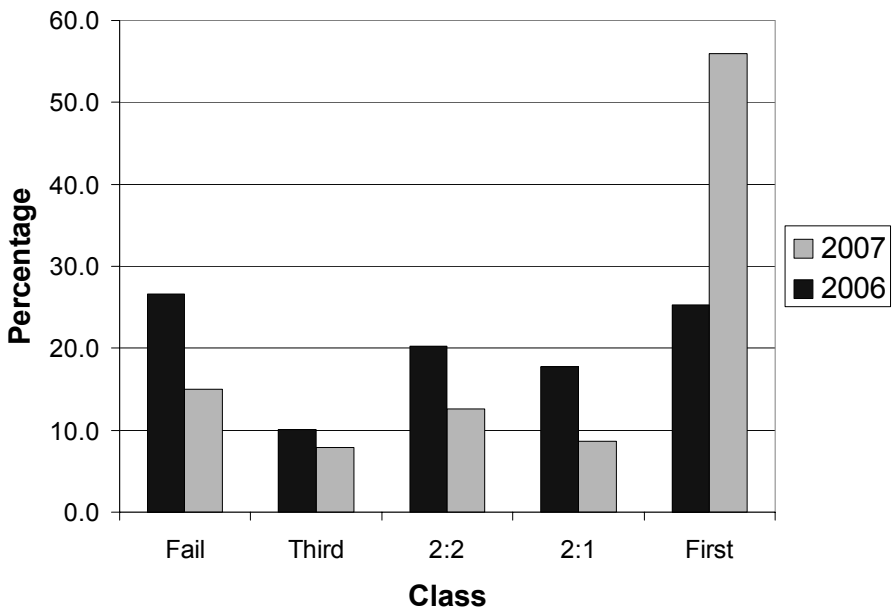

Figure 6: Bar Chart showing percentage of students achieving each degree class in the retrosynthesis exam for 2006 and 2007

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